APPLICATION

FOR

UNITED STATES LETTERS PATENT

TITLE: HIGH FREQUENCY DROPLET EJECTION DEVICE AND METHOD

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HIGH FREQUENCY DROPLET EJECTION
DEVICE AND METHOD

TECHNICAL FIELD

This invention relates to droplet ejection devices and methods for driving droplet ejection devices.

BACKGROUND

5   Droplet ejection devices are used for a variety of purposes, most commonly for printing images on various media. They are often referred to as ink jets or ink jet printers. Drop-on-demand droplet ejection devices are used in many applications because of their flexibility and economy. Drop-on-demand devices eject a single droplet in response to a specific signal, usually an electrical waveform, or waveform.

10   Droplet ejection devices typically include a fluid path from a fluid supply to a nozzle path. The nozzle path terminates in a nozzle opening from which drops are ejected. Droplet ejection is controlled by pressurizing fluid in the fluid path with an actuator, which may be, for example, a piezoelectric deflector, a thermal bubble jet generator, or an electro-statically deflected element. A typical printhead has an array of fluid paths with corresponding nozzle openings and associated actuators, and droplet ejection from each nozzle opening can be

15   independently controlled. In a drop-on-demand printhead, each actuator is fired to selectively eject a droplet at a specific target pixel location as the printhead and a substrate are moved relative to one another. In high performance printheads, the nozzle openings typically have a diameter of 50 micron or less, e.g., around 25 microns, are separated at a pitch of 100-300

20   nozzles/inch, have a resolution of 100 to 300 dpi or more, and provide droplet sizes of about 1 to 100 picoliters (pl) or less. Droplet ejection frequency is typically 10-100 kHz or more but may be lower for some applications.

Hoisington et al. U.S. 5,265,315, the entire contents of which is hereby incorporated by reference, describes a printhead that has a semiconductor printhead body and a piezoelectric

25   actuator. The printhead body is made of silicon, which is etched to define fluid chambers. Nozzle openings are defined by a separate nozzle plate, which is attached to the silicon body. The piezoelectric actuator has a layer of piezoelectric material, which changes geometry, or bends, in response to an applied voltage. The bending of the piezoelectric layer pressurizes ink

in a pumping chamber located along the ink path. Deposition accuracy is influenced by a number of factors, including the size and velocity uniformity of drops ejected by the nozzles in the head and among multiple heads in a device. The droplet size and droplet velocity uniformity are in turn influenced by factors such as the dimensional uniformity of the ink paths, acoustic

5   interference effects, contamination in the ink flow paths, and the actuation uniformity of the actuators.

Because drop-on-demand ejectors are often operated with either a moving target or a moving ejector, variations in droplet velocity lead to variations in position of drops on the media. These variations can degrade image quality in imaging applications and can degrade system

10   performance in other applications. Variations in droplet volume lead to variations in spot size in images, or degradation in performance in other applications. For these reasons, it is usually preferable for droplet velocity, droplet volume and droplet formation characteristics to be as constant as possible throughout the operating range of an ejector.

Droplet ejector producers apply various techniques to improve frequency response,

15   however, the physical requirements of firing drops in drop-on-demand ejectors may limit the extent to which frequency response can be improved. "Frequency response" refers to the characteristic behavior of the ejector determined by inherent physical properties that determine ejector performance over a range of droplet ejection frequencies. Typically, droplet velocity, droplet mass and droplet volume vary as a function of frequency of operation; often, droplet

20   formation is also affected. Typical approaches to frequency response improvement may include reducing the length of the flow passages in the ejectors to increase the resonant frequency, increase in fluidic resistance of the flow passages to increase damping, and impedance tuning of internal elements such as nozzles and restrictors.

SUMMARY

25   Drop-on-demand droplet ejection devices may eject drops at any frequency, or combination of frequencies, up to a maximum capability of the ejection device. When operating over a wide range of frequencies, however, their performance can be affected by the frequency response of the ejector.

One way to improve the frequency response of a droplet ejector is to use a multipulse

30   waveform with sufficiently high frequency to form a single droplet in response to the waveform.

Note that the multipulse waveform frequency typically refers to the inverse of the pulse periods in the waveform, as opposed to the droplet ejection frequency referred to earlier, and to which the "frequency response" pertains. Multipulse waveforms of this type form single drops in many ejectors because the pulse frequency is high and the time between pulses is short relative to droplet formation time parameters.

In order to improve the frequency response, the waveform should generate a single large droplet, as opposed to multiple smaller drops that can form in response to a multipulse waveform. When a single large droplet is formed, the energy input from the individual pulses is averaged over the multipulse waveform. The result is that the effect of fluctuations in energy imparted to the fluid from each pulse is reduced. Thus, droplet velocity and volume remain more constant throughout the operating range.

Several pulse design parameters can be optimized to assure that a single droplet is formed in response to a multipulse waveform. In general terms, these include the relative amplitudes of individual segments of each pulse, the relative pulse widths of each segment, and the slew rate of each portion of the waveform. In some embodiments, single drops can be formed from multipulse waveforms where the voltage amplitude of each pulse gets progressively larger. Alternatively, or additionally, singles drops can result from multipulse waveforms where the time between the successive pulses is short relative to the total pulse width. The multipulse waveform can have little or no energy at frequencies corresponding to the jet natural frequency and its harmonics.

In general, in a first aspect, the invention features a method for driving a droplet ejection device having an actuator, including applying a multipulse waveform that includes two or more drive pulses to the actuator to cause the droplet ejection device to eject a single droplet of a fluid, wherein a frequency of the drive pulses is greater than a natural frequency, f_j, of the droplet ejection device.

Embodiments of the method can include one or more of the following features and/or features of other aspects. In some embodiments, the multipulse waveform has two drive pulses, three drive pulses, or four drive pulses. The pulse frequencies can be greater than about $1.3 f_j$, $1.5 f_j$. The pulse frequency can be between about $1.5 f_j$ and about $2.5 f_j$, such as between about $1.8 f_j$ and about $2.2 f_j$. The two or more pulses can have the same pulse period. The individual pulses can have different pulse periods. The two or more pulses can include one or more bipolar

pulses and/or one or more unipolar pulses. In some embodiments, the droplet ejection device includes a pumping chamber and the actuator is configured to vary the pressure of the fluid in the pumping chamber in response to the drive pulses. Each pulse can have an amplitude corresponding to a maximum or minimum voltage applied to the actuator, and the amplitude of

5   at least two of the pulses can be substantially the same. Each pulse can have an amplitude corresponding to a maximum or minimum voltage applied to the actuator, and the amplitude of at least two of the pulses can be different. For example, the amplitude of each subsequent pulse in the two or more pulses can be greater than the amplitude of earlier pulses. The droplet ejection device can be an ink jet.

10   In general, in a further aspect, the invention features a method that includes driving a droplet ejection device with a waveform including one or more pulses each having a period less than about 20 microseconds to cause the droplet ejection device to eject a single droplet in response to the pulses.

Embodiments of the method can include one or more of the following features and/or

15   features of other aspects. The one or more pulses can each have a period less than about 12 microseconds, 10 microseconds, 8 microseconds, or 5 microseconds.

In general, in another aspect, the invention features a method that includes driving a droplet ejection device with a multipulse waveform including two or more pulses each having a pulse period less than about 25 microseconds to cause the droplet ejection device to eject a single

20   droplet in response to the two or more pulses.

Embodiments of the method can include one or more of the following features and/or features of other aspects. The two or more pulses can each have a pulse period less than about 12 microseconds, 10 microseconds, 8 microseconds, or 5 microseconds. In some embodiments, the droplet has a mass between about 1 picoliter and 100 picoliters. In other embodiments, the

25   droplet has a mass between about 5 picoliters and 200 picoliters. In still further embodiments, the droplet has a mass between about 50 picoliters and 1000 picoliters.

In general, in a further aspect, the invention features an apparatus, including a droplet ejection device having a natural frequency, f_j, and drive electronics coupled to the droplet ejection device, wherein during operation the drive electronics drive the droplet ejection device

30   with a multipulse waveform that includes a plurality of drive pulses having a frequency greater than f_j. The harmonic content of the plurality of drive pulses at f_j can be less than about 50%(

e.g., less than about 25%, 10%) of the harmonic content of the plurality of the drive pulses at f_{max}, the frequency of maximum content.

Embodiments of the apparatus can include one or more of the following features and/or features of other aspects. During operation, the droplet ejection device can eject a single droplet in response to the plurality of pulses. The droplet ejection device can be an ink jet. In another aspect, the invention features an ink jet printhead including the aforementioned ink jet.

In general, in a further aspect, the invention features a method for driving a droplet ejection device having an actuator, including applying a multipulse waveform that includes two or more drive pulses to the actuator to cause the droplet ejection device to eject a droplet of a fluid, wherein at least about 60% of the droplet's mass is included within a radius, r, of a point in the droplet, where r corresponds to a radius of a perfectly spherical droplet given by

$$r = \sqrt[3]{\frac{3}{4\pi} \frac{m_d}{\rho}} ,$$

where m_d is the droplet's mass and ρ is the fluid density.

Embodiments of the method can include one or more of the following features and/or features of other aspects. The droplet can have a velocity of at least about 4 ms^{-1} (e.g., at least about 6 ms^{-1}, 8 ms^{-1} or more. A frequency of the drive pulses can be greater than a natural frequency, f_j, of the droplet ejection device. At least about 80% (e.g., at least about 90%) of the droplet's mass can be included within r of a point in the droplet.

Embodiments of the invention may have one or more of the following advantages.

The techniques disclosed herein may be used to improve frequency response performance of droplet ejection devices. Variations in the velocity of drops ejected from a droplet ejector, or jet, as a function of firing rate, can be significantly reduced. Variations in the volume of drops ejected from a droplet ejector, as a function of firing rate, can be significantly reduced. The reductions in velocity errors can lead to reduced droplet placement errors, and to improved images in imaging applications. The reduction in volume variation can lead to improved quality in non-imaging applications, and improved images in imaging applications.

These methods can also be used to improve frequency dependent ejector performance in an application, by specifying a droplet ejector design that produces drops that are, e.g., 1.5 - 4 or more times smaller (in volume) than is required for the application. Then by applying these techniques, the ejector can produce the droplet size required for the application. Accordingly, the

techniques disclosed herein may be used to provide large droplet sizes from small droplet ejection devices and may be used to generate a large range of droplet sizes from a droplet ejection device. The large range of droplet sizes achievable using disclosed techniques can facilitate gray scale images with a large range of gray levels in ink jet printing applications.

5   These techniques may reduce droplet tail size, thereby reducing image degradation that can occur due to droplet placement inaccuracies associated with large ink droplet tails in ink jet printing applications. These techniques can reduce inaccuracies by achieving a large droplet volume without multiple drops, because a single large droplet will put all of the fluid in one location on a moving substrate, as opposed to multiple locations when the substrate is moving relative to the

10   ejection device. Further benefit may be obtained because single large drops can travel further and straighter than several small drops.

The details of one or more embodiments of the invention are set forth in the accompanying drawings and the description below. Other features, objects, and advantages of the invention will be apparent from the description and drawings, and from the claims.

15   **DESCRIPTION OF DRAWINGS**

FIG. 1 is a schematic diagram of an embodiment of a printhead.

FIG. 2A is a cross-sectional view of an embodiment of an ink jet.

FIG. 2B is a cross-sectional view of an actuator of the ink jet shown in FIG. 2A.

FIG. 3 is a plot of normalized droplet velocity versus time between fire pulses for droplet

20   ejection from a droplet ejector firing at a constant rate.

FIG. 4A is a plot of voltage versus normalized time for a bi-polar waveform for driving a droplet ejector.

FIG. 4B is a plot of a unipolar waveform for driving a droplet ejector.

FIG. 5A – 5E are schematic diagrams showing the ejection of ink from an orifice of an

25   ink jet in response to a multipulse waveform.

FIG. 6A – 6I are photographs showing the ejection of ink from an orifice of an ink jet in response to a multipulse waveform.

FIG. 7 is a plot of amplitude versus frequency content of a single four microsecond trapezoidal waveform determined using a Fourier transform of the waveform.

FIG. 8 is a plot showing the frequency response for an 80 picoliter droplet ejector showing the variation in droplet velocity vs. jet firing frequency from 4 to 60 kilohertz when fired with a single trapezoidal waveform.

FIG. 9 is a plot of a calculated voltage equivalent time response for an exemplary 80 picoliter droplet ejector.

FIG. 10 is a plot of the Fourier transforms of the ejector time response and a four pulse waveform for the exemplary 80 picoliter droplet ejector.

FIG. 11 is a plot comparing the frequency response of two ejectors that form similar size droplets.

FIG. 12 is a plot of voltage versus time for a multipulse waveform in which there is a delay period between adjacent pulses.

FIG. 13 is a plot of voltage versus time for a drive signal including multiple multipulse waveforms.

FIG. 14 is a photograph showing the ejection of multiple drops from an ink jet orifice using a multipulse waveform.

FIG. 15A is a photograph showing droplet ejection using a multipulse waveform. Ejection frequency is 10 kHz and droplet velocity is about $8ms^{-1}$.

FIG. 15B is a photograph showing droplet ejection using a single pulse waveform. Ejection frequency is 10 kHz and droplet velocity is about $8ms^{-1}$.

FIG. 16A is a photograph showing droplet ejection using a multipulse waveform. Ejection frequency is 20 kHz and droplet velocity is about $8ms^{-1}$.

FIG. 16B is a photograph showing droplet ejection using a single pulse waveform. Ejection frequency is 20 kHz and droplet velocity is about $8ms^{-1}$.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

Referring to FIG. 1, a print head 12 includes multiple (e.g., 128, 256 or more) ink jets 10 (only one is shown on FIG. 1), which are driven by electrical drive pulses provided over signal lines 14 and 15 and distributed by on-board control circuitry 19 to control firing of ink jets 10. An external controller 20 supplies the drive pulses over lines 14 and 15 and provides control data and logic power and timing over additional lines 16 to on-board control circuitry 19. Ink jetted

by ink jets 10 can be delivered to form one or more print lines 17 on a substrate 18 that moves relative to print head 12 (e.g., in the direction indicated by arrow 21). In some embodiments, substrate 18 moves past a stationary print head 12 in a single pass mode. Alternatively, print head 12 can also move across substrate 18 in a scanning mode.

5   Referring to FIG. 2A (which is a diagrammatic vertical section), each ink jet 10 includes an elongated pumping chamber 30 in an upper face of a semiconductor block 21 of print head 12. Pumping chamber 30 extends from an inlet 32 (from a source of ink 34 along the side) to a nozzle flow path in a descender passage 36 that descends from an upper surface 22 of block 21 to a nozzle 28 opening in a lower layer 29. The nozzle size may vary as desired. For example, the

10   nozzle can be on the order of a few microns in diameter (e.g., about 5 microns, about 8 microns, 10 microns) or can be tens or hundreds of microns in diameter (e.g., about 20 microns, 30 microns, 50 microns, 80 microns, 100 microns, 200 microns or more). A flow restriction element 40 is provided at the inlet 32 to each pumping chamber 30. A flat piezoelectric actuator 38 covering each pumping chamber 30 is activated by drive pulses provided from line 14, the timing

15   of which are controlled by control signals from on-board circuitry 19. The drive pulses distort the piezoelectric actuator shape and thus vary the volume in chamber 30 drawing fluid into the chamber from the inlet and forcing ink through the descender passage 36 and out the nozzle 28. Each print cycle, multipulse drive waveforms are delivered to activated jets, causing each of those jets to eject a single droplet from its nozzle at a desired time in synchronism with the

20   relative movement of substrate 18 past the print head device 12.

         Referring also to FIG. 2B, flat piezoelectric actuator 38 includes a piezoelectric layer 40 disposed between a drive electrode 42 and a ground electrode 44. Ground electrode 44 is bonded to a membrane 48 (e.g., a silica, glass or silicon membrane) by a bonding layer 46. During operation, drive pulses generate an electric field within piezoelectric layer 40 by applying a

25   potential difference between drive electrode 42 and ground electrode 44. Piezoelectric layer 40 distorts actuator 38 in response to the electric field, thus changing the volume of chamber 30.

         Each ink jet has a natural frequency, f_j, which is related to the inverse of the period of a sound wave propagating through the length of the ejector (or jet). The jet natural frequency can affect many aspects of jet performance. For example, the jet natural frequency typically affects

30   the frequency response of the printhead. Typically, the jet velocity remains constant (e.g., within 5% of the mean velocity) for a range of frequencies from substantially less than the natural

frequency (e.g., less than about 5% of the natural frequency) up to about 25% of the natural frequency of the jet. As the frequency increases beyond this range, the jet velocity begins to vary by increasing amounts. It is believed that this variation is caused, in part, by residual pressures and flows from the previous drive pulse(s). These pressures and flows interact with the current drive pulse and can cause either constructive or destructive interference, which leads to the droplet firing either faster or slower than it would otherwise fire. Constructive interference increases the effective amplitude of a drive pulse, increasing droplet velocity. Conversely, destructive interference decreases the effective amplitude of a drive pulse, thereby decreasing droplet velocity.

The pressure waves generated by drive pulses reflect back and forth in the jet at the natural or resonant frequency of the jet. The pressure waves, nominally, travel from their origination point in the pumping chamber, to the ends of the jet, and back under the pumping chamber, at which point they would influence a subsequent drive pulse. However, various parts of the jet can give partial reflections adding to the complexity of the response.

In general, the natural frequency of an ink jet varies as a function of the ink jet design and physical properties of the ink being jetted. In some embodiments, the natural frequency of ink jet 10 is more than about 15 kHz. In other embodiments, the natural frequency of ink jet 10 is about 30 to 100 kHz, for example about 60 kHz or 80 kHz. In still further embodiments, the natural frequency is equal to or greater than about 100 kHz, such as about 120 kHz or about 160 kHz.

One way to determine the jet natural frequency is from the jet velocity response, which can readily be measured. The periodicity of droplet velocity variations corresponds to the natural frequency of the jet. Referring to FIG. 3, the periodicity of droplet velocity variations can be measured by plotting droplet velocity versus the inverse of the pulse frequency, and then measuring the time between the peaks. The natural frequency is $1/\tau$, where τ is the time between local extrema (i.e., between adjacent maxima or adjacent minima) of the velocity vs. time curve. This method can be applied using electronic data reduction techniques, without actually plotting the data.

Droplet velocity can be measured in a variety of ways. One method is to fire the ink jet in front of a high-speed camera, illuminated by a strobe light such as an LED. The strobe is synchronized with the droplet firing frequency so that the drops appear to be stationary in a video

of the image. The image is processed using conventional image analysis techniques to determine the location of the droplet heads. These are compared with the time since the droplet was fired to determine the effective droplet velocity. A typical system stores data for velocity as a function of frequency in a file system. The data can be analyzed by an algorithm to pick out the peaks or

5 analytically derived curves can be fit to the data (parameterized by, e.g., frequency, damping, and/or velocity). Fourier analysis can also be used to determine jet natural frequency.

During operation, each ink jet may jet a single droplet in response to a multipulse waveform. An example of a multipulse waveform is shown in FIG. 4A. In this example, multipulse waveform 400 has four pulses. Each multipulse waveform would typically be

10 separated from subsequent waveforms by a period corresponding to an integer multiple of the jetting period (i.e., the period corresponding to the jetting frequency). Each pulse can be characterized as having a "fill" ramp, which corresponds to when the volume of the pumping element increases, and a "fire" ramp (of opposite slope to the fill ramp), which corresponds to when the volume of the pumping element decreases. In multipulse waveform 400 there is a

15 sequence of fill and fire ramps. Typically, the expansion and contraction of the volume of the pumping element creates a pressure variation in the pumping chamber that tends to drive fluid out of the nozzle.

Each pulse has a pulse period, τ_p, corresponding to the time from the start of the individual pulse segment to the end of that pulse segment. The total period of the multipulse

20 waveform is the sum of the four pulse periods. The waveform frequency can be determined, approximately, as the number of pulses divided by the total multipulse period. Alternatively, or additionally, Fourier analysis can be used to provide a value for the pulse frequency. Fourier analysis provides a measure of the harmonic content of the multipulse waveform. The pulse frequency corresponds to a frequency, f_{max}, at which the harmonic content is greatest (i.e., the

25 highest non-zero energy peak in the Fourier spectrum). Preferably, the pulse frequency of the drive waveform is greater than the natural frequency, f_j, of the jet. For example, the pulse frequency can be between about 1.1 and 5 times the jet natural frequency, such as between about 1.3 and 2.5 times f_j (e.g., between about 1.8 and 2.3 times f_j, such as about twice f_j). In some embodiments, the pulse frequency can be equal to a multiple of the jet natural frequency, such as

30 approximately two, three or four times the natural frequency of the jet.

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In the present embodiment, the pulses are bipolar. In other words, multipulse waveform 400 includes portions of negative (e.g., portion 410) and positive polarity (e.g., portion 420). Some waveforms may have pulses that are exclusively one polarity. Some waveforms may include a DC offset. For example, FIG. 4B shows a multipulse waveform that includes exclusively unipolar pulses. In this waveform, the pulse amplitudes and widths increase progressively with each pulse.

The volume of a single ink droplet ejected by a jet in response to a multipulse waveform increases with each subsequent pulse. The accumulation and ejection of ink from the nozzle in response to a multipulse waveform is illustrated in FIG. 5A –FIG. 5E. Prior to the initial pulse, ink within ink jet 10 terminates at a meniscus 510 which is curved back slightly (due to internal pressure) from an orifice 528 of nozzle 28 (see FIG. 5A). Orifice 528 has a minimum dimension, D. In embodiments where orifice 528 is circular, for example, D is the orifice diameter. In general, D can vary according to jet design and droplet size requirements. Typically, D is between about 10 μm and 200 μm, e.g., between about 20 μm and 50 μm. The first pulse forces an initial volume of ink to orifice 528, causing an ink surface 520 to protrude slightly from nozzle 28 (see FIG. 5B). Before the first partial droplet can either separate or retract, the second pulse forces another volume of ink through nozzle 28, which adds to the ink protruding from nozzle 28. The ink from the second and third pulses, as shown in FIG. 5C and FIG. 5D, respectively, increases the volume of the droplet, and adds momentum. Generally, the volumes of ink from the successive pulses, can be seen as bulges in the droplet that is forming, as shown in FIG. 5C and FIG. 5D Ultimately, nozzle 28 ejects a single droplet 530 with the fourth pulse, and meniscus 510 returns to its initial position (FIG. 5E). FIG. 5E also shows a very thin tail 544 connecting the droplet head to the nozzle. The size of this tail can be substantially smaller than would occur for drops formed using a single pulse and a larger nozzle.

A sequence of photographs illustrating droplet ejection is shown in FIG. 6A – 6I. In this example, the ink jet has a circular orifice with a 50 μm diameter. The ink jet was driven by a four-pulse multipulse waveform at a pulse frequency of approximately 60 kHz, generating a 250 picoliter droplet. Images were captured every six microseconds. The volume of ink protruding from the orifice increases with each successive pulse (FIG. 6A - 6G). FIG. 6H – 6I show the trajectory of the ejected droplet. Note that the ink jet surface is reflective, resulting in a mirror image of the droplet in the top half of each image.

The formation of a single large droplet with multiple fire pulses can reduce the volume of the fluid in the tail. Droplet "tail" refers to the filament of fluid connecting the droplet head, or leading part of the droplet to the nozzle until tail breakoff occurs. Droplet tails often travel slower than the lead portion of the droplet. In some cases, droplet tails can form satellites, or separate droplets, that do not land at the same location as the main body of the droplet. Thus, droplet tails can degrade overall ejector performance.

It is believed that droplet tails can be reduced by multipulse droplet firing because the impact of successive volumes of fluid changes the character of droplet formation. Later pulses of the multipulse waveform drive fluid into fluid driven by earlier pulses of the multipulse waveform, which is at the nozzle exit, forcing the fluid volumes to mix and spread due to their different velocities. This mixing and spreading can prevent a wide filament of fluid from connecting at the full diameter of the droplet head, back to the nozzle. Multipulse drops typically have either no tails or a very thin filament, as opposed to the conical tails often observed in single pulse drops. FIG. 15A and 15B compare droplet formation of 80 picoliter drops using multipulsing of a 20 picoliter jet design and single pulsing of an 80 picoliter jet design at 10 kHz firing rates and 8 m/s droplet velocity. Similarly, FIG. 16A and 16B compare droplet formation of 80 picoliter drops using multipulsing of a 20 picoliter jet design and single pulsing of an 80 picoliter jet design at 20 kHz firing rates and 8 m/s droplet velocity. These figures illustrate reduced tail formation for the multipulsed droplet.

As discussed previously, one method of determining the natural frequency of a jet is to perform a Fourier analysis of the jet frequency response data. Because of the non-linear nature of the droplet velocity response of a droplet ejector, the frequency response is linearized, as explained subsequently, to improve the accuracy of the Fourier analysis.

In a mechanically actuated droplet ejector, such as a piezo-driven drop-on-demand inkjet, the frequency response behavior is typically assumed to be a result of residual pressures (and flows) in the jet from previous drops that were fired. Under ideal conditions, pressure waves traveling in a channel decay in a linear fashion with respect to time. Where the amplitude of the pressure waves can be approximated from the velocity data, an equivalent frequency response can be derived that represents more linearly behaving pressure waves in the jet.

There are a number of ways to determine pressure variations in a chamber. In some droplet ejectors, such as piezo-driven ejectors, the relationship between applied voltage and

pressure developed in the pumping chamber can often be assumed linear. Where non-linearities exist, they can be characterized by measurement of piezo deflection, for example. In some embodiments, pressure can be measured directly.

Alternatively, or additionally, residual pressure in a jet can be determined from the velocity response of the jet. In this approach, velocity response is converted to a voltage equivalent frequency response by determining the voltage required to fire the droplet at the measured velocity from a predetermined function. An example of this function is a polynomial, such as

$$V = Av^2 + Bv + C,$$

where V is the voltage, v is the velocity and A, B, and C are coefficients, which can be determined experimentally. This conversion provides an equivalent firing voltage that can be compared to the actual firing voltage. The difference between the equivalent firing voltage and the actual firing voltage is a measure of residual pressure in the jet.

When driven continuously at any particular jetting frequency, the residual pressures in the jet are the result of a series of pulse inputs spaced in time by the fire period (i.e., the inverse of the fire frequency), with the most recent pulse one fire period in the past. The voltage equivalent amplitude of the frequency response is plotted against the inverse of the frequency of the waveforms. This is equivalent to comparing the velocity response to the time since firing. A plot of the voltage equivalent versus time between pulses is, therefore, a representation of the decay of the pressure waves in the jet as a function of time. The actual driving function at each point in the voltage equivalent response versus time plot is a series of pulses at a frequency equal to the multiplicative inverse of the time at that point. If the frequency response data is taken at appropriate intervals of frequency, the data can be corrected to represent the response to a single pulse.

The response can be represented mathematically by

$$R(t) = P(t) + P(2t) + P(3t) + \ldots,$$

13

where $R(t)$ is the jet response to a series of pulses separated by a period t and $P(t)$ is the jet response to a single pulse input at time t. Assuming that $R(t)$ is a linear function of the inputs, the response equation can be manipulated algebraically to solve for $P(t)$ given a measured $R(t)$. Typically, because the residual energy in the jet decays with time, calculating a limited number

5   of response times provides a sufficiently accurate result.

The above analysis can be based on frequency response data taken on a test stand that illuminates the droplet with a stroboscopic light and the jet is fired continuously so that the imaging/measurement system measures a series of pulses fired at a given frequency. Alternatively, one can repeatedly fire a jet with pairs of pulses spaced with specific time

10   increments between them. The pairs of pulses are fired with sufficient delay between them so that residual energy in the jet substantially dies out before the next pair is fired. This method can eliminate the need to account for earlier pulses when deriving the response to a single pulse.

The derived frequency response is typically a reasonable approximation to a transfer function. For these tests, the pulse input to the jet is narrow relative to the frequencies that must

15   be measured. Typically, the Fourier transform of a pulse shows frequency content at all frequencies below the inverse of the pulsewidth. The amplitude of these frequencies decreases to zero at a frequency equal to the inverse of the pulsewidth, assuming the pulse has a symmetrical shape. For example, FIG. 7 shows a Fourier transform of a four microsecond trapezoidal waveform that decays to zero at about 250 kHz.

20   In order to determine the frequency response of an ejector using a Fourier transform, data should be obtained of the ejector droplet velocity as a function of frequency. The ejector should be driven with a simple fire pulse, whose pulse width is as short as feasible with respect to the anticipated ejector natural period, which is equal to the inverse of the ejector natural frequency. The short period of the fire pulse assures that harmonic content of the fire pulse extends to high

25   frequency, and thus the jet will respond as if driven by an impulse, and the frequency response data will not be substantially influenced by the fire pulse itself. FIG. 8 shows an example of a frequency response curve for a particular configuration of an 80 picoliter droplet ejector.

Data relating the voltage required to fire drops as a function of the velocity of the drops should also be acquired. This data is used to linearize the ejector response. In most droplet

30   ejectors, the relationship between droplet velocity and voltage is non-linear, especially at low voltages (i.e., for low velocities). If the Fourier analysis is performed directly on the velocity

data, it is likely that the frequency content will be distorted by the non-linear relationship between droplet velocity and pressure energy in the jet. A curve-fit such as a polynomial can be made to represent the voltage/velocity relationship, and the resulting equation can be used to transform the velocity response into a voltage equivalent response.

5   After transforming the velocity frequency response to a voltage, the baseline (low frequency) voltage is subtracted. The resulting value represents the residual drive energy in the jet. This is also transformed into a time response, as described previously. FIG. 9 shows an example of a voltage equivalent response as a function of pulse delay time. This curve evidences an exponential decay envelope of the frequency response.

10   The voltage equivalent time response data can be analyzed using a Fourier transform. FIG. 10 shows the results of a Fourier analysis on the ejector time response and the Fourier analysis of a four-pulse waveform. The dark line represents the Fourier transform of the droplet ejector (jet) time response. In the present example, this shows a strong response at 30 kHz, which is the fundamental natural frequency for this ejector. It also shows a significant second 15   harmonic at 60 kHz.

       FIG. 10 also shows the Fourier transform of a four-pulse waveform designed to drive the same ejector. As the figure shows, the waveform has low energy at the fundamental natural frequency of the ejector. Because the energy in the waveform is low at the natural frequency of the ejector, the ejector's resonant response is not substantially excited by the waveform.

20   FIG. 11 shows frequency response data for two different ejectors. The ejectors fire similar size drops. The darker line is data for the ejector used in the examples above fired with a four-pulse waveform. The lighter lines shows data for an ejector firing a similar-sized droplet with a single pulse waveform. The single pulse waveform response varies significantly more than the multipulse waveform.

25   Some ink jet configurations, with particular inks, do not produce a velocity vs. time curve that readily facilitates determination of the natural frequency. For example, inks that heavily damp reflected pressure waves (e.g., highly viscous inks) can reduce the amplitude of the residual pulses to a level where little or no oscillations are observed in the velocity vs. time curve. In some cases, a heavily damped jet will fire only at very low frequencies. Some jet 30   firing conditions produce frequency response plots that are very irregular, or show two strong frequencies interacting so that identifying a dominant natural frequency is difficult. In such

cases, it may be necessary to determine natural frequency by another method. One such method is to use a theoretical model to calculate the natural frequency of the jet from, e.g., the physical dimensions, material properties and fluid properties of the jet and ink.

Calculating the natural frequency involves determining the speed of sound in each section

5   of the jet, then calculating the travel time for a sound wave, based on each section's length. The total travel time, τ_{travel}, is determined by adding all the times together, and then doubling the total to account for the round trip the pressure wave makes through each section. The inverse of the travel time, τ_{travel}^{-1}, is the natural frequency, f_j.

The speed of sound in a fluid is a function of the fluid's density and bulk modulus, and

10   can be determined from the equation

$$c_{sound} = \sqrt{\frac{B_{mod}}{\rho}}$$

where c_{sound} is the speed of sound in meters per second, B_{mod} is the bulk modulus in pascals, and

15   ρ is the density in kilograms per cubic meter. Alternatively, the bulk modulus can be deduced from the speed of sound and the density, which may be easier to measure.

In portions of the ink jet where structural compliance is large, one should include the compliance in the calculation of sound speed to determine an effective bulk modulus of the fluid. Typically, highly compliant portions include the pumping chamber because the pumping element

20   (e.g., the actuator) is usually necessarily compliant. It may also include any other portion of the jet where there is a thin wall, or otherwise compliant structure surrounding the fluid. Structural compliance can be calculated using, e.g., a finite element program, such as ANSYS® software (commercially available from Ansys Inc., Canonsburg, PA), or by careful manual calculations.

In a flow channel, the compliance of a fluid, C_F, can be calculated from the actual bulk

25   modulus of the fluid and the channel volume, V, where:

$$C_F = \frac{V}{B_{mod}}$$

The units of the fluid compliance are cubic meters per pascal.

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In addition to the fluid compliance, the effective speed of sound in a channel should be adjusted to account for any compliance of the channel structure. The compliance of the channel structure (e.g., channel walls) can be calculated by various standard mechanical engineering formulas'. Finite element methods can be also used for this calculation, especially where structures are complex. The total compliance of the fluid, C_{TOTAL}, is given by:

$$C_{TOTAL} = C_F + C_S$$

where C_S is the compliance of the structure. The effective speed of sound, $c_{soundEff}$, in the fluid in each section of the inject can be determined from

$$c_{soundEff} = \sqrt{\frac{B_{modEff}}{\rho}},$$

where B_{modEff} is the effective bulk modulus, which can be calculated from total compliance and volume of the flow channel:

$$B_{modEff} = \frac{V}{C_{TOTAL}}.$$

The frequency response of a droplet ejector can be improved through appropriate design of the waveform used to drive the ejector. Frequency response improvement can be accomplished by driving the droplet ejector with a fire pulse that is tuned to reduce or eliminate residual energy in the ejector, after the droplet is ejected. One method for accomplishing this is to drive the ejector with a series of pulses whose fundamental frequency is a multiple of the resonant frequency of the ejector. For example, the multipulse frequency can be set to approximately twice the resonant frequency of the jet. A series of pulses (e.g., 2 - 4 pulses) whose pulse frequency is two to four times the resonant frequency of the jet has extremely low energy content at the resonant frequency of the jet. The amplitude of the Fourier transform of the waveform at the resonant frequency of the jet, as seen in FIG. 10, is a good indicator of the relative energy in the waveform. In this case, the multipulse waveform has about 20 % of the

amplitude of the envelope, defined by the peaks in the Fourier transform, at the jet natural frequency.

As discussed previously, the multipulse waveform preferably results in the formation of a single droplet. The formation of a single droplet assures that the separate drive energies of the individual pulses are averaged in the droplet that is formed. Averaging the drive energies of the pulses is, in part, responsible for the flattening of the frequency response of the droplet ejector. Where the pulses are timed to a multiple of the resonant period of the ejector (e.g., 2 – 4 times the resonant period), the multiple pulses span a period that is an integral multiple of the ejector's resonant period. Because of this timing, residual energy from previous droplet firings is largely self-canceling, and therefore has little influence on the formation of the current droplet.

The formation of a single droplet from a multipulse waveform depends on the amplitudes and timing of the pulses. No individual droplet should be ejected by the first pulses of the pulse train, and the final volume of fluid that is driven by the final pulse should coalesce with the initial volume forming at the nozzle with sufficient energy to ensure droplet separation from the nozzle and formation of a single droplet. Individual pulse widths should be short relative to the individual droplet formation time. Pulse frequency should be high relative to droplet breakup criteria.

The first pulses of the pulse train can be shorter in duration than the later pulses. Shorter pulses have less drive energy than longer pulses of the same amplitude. Provided the pulses are short relative to an optimum pulse width (corresponding to maximum droplet velocity), the volume of fluid driven by the later (longer) pulses will have more energy than earlier pulses. The higher energy of later fired volumes means they coalesce with the earlier fired volumes, resulting in a single droplet. For example, in a four pulse waveform, pulse widths may have the following timings: first pulse width 0.15 - 0.25; second pulse width 0.2 - 0.3; third pulse width 0.2 - 0.3; and fourth pulse width 0.2 - 0.3, where the pulse widths represent decimal fractions of the total pulse width.

In some embodiments, pulses have equal width but different amplitude. Pulse amplitudes can increase from the first pulse to the last pulse. This means that the energy of the first volume of fluid delivered to the nozzle will be lower than the energy of later volumes. Each volume of fluid may have progressively larger energy. For example, in a four pulse waveform, the relative amplitudes of the individual fire pulses may have the following values: first pulse amplitude 0.25

- 1.0 (e.g., 0.73); second pulse amplitude 0.5 - 1.0 (e.g., 0.91); third pulse amplitude 0.5 - 1.0 (e.g., 0.95); and fourth pulse amplitude 0.75 to 1.0 (e.g., 1.0).

Other relationships are also possible. For example, in some embodiments, the later pulse can have lower amplitude than the first pulses.

5   Values for pulse widths and amplitudes can be determined empirically, using droplet formation, voltage and current requirements, jet sustainability, resultant jet frequency response and other criteria for evaluation of a waveform. Analytical methods can also be used for estimating droplet formation time for single drops, and droplet breakup criteria.

Preferably, the tail breakoff time is substantially longer than the period between fire

10   pulses. The implication is that the droplet formation time is significantly longer than the pulse time and thus individual drops will not be formed.

In particular, for single droplet formation, two criteria can be evaluated to estimate tail breakoff time or droplet formation time. A time parameter, T_0, can be calculated from the ejector geometry and fluid properties (see, e.g., Fromm, J. E., "Numerical Calculation of the Fluid

15   Dynamics of Drop-on-demand Jets," IBM J. Res. Develop., Vol. 28 No. 3, May 1984). This parameter represents a scaling factor that relates nozzle geometry and fluid properties to droplet formation time and is derived using numerical modeling of droplet formation.

T_0 is defined by the equation:

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$$T_0 = (\rho r^3 / \sigma)^{1/2}.$$

Here, r is the nozzle radius (e.g., 50 microns), ρ is the fluid density (e.g., 1 gm/cm^3) and σ is the fluid surface tension (e.g., 30 dyn/cm). These values correspond to the dimensions of a jet that would produce an 80 picoliter droplet for a typical test fluid (e.g., a mixture of water and glycol).

25   Typically, the pinch-off time varies from about two to four times T_0, as explained in the Fromm reference. Thus, by this criterion, the breakoff time would be 130 - 260 microseconds for the parameter value examples mentioned.

Another calculation of tail breakoff time, discussed by Mills, R.N., Lee F.C., and Talke F.E., in "Drop-on-demand Ink Jet Technology for Color Printing," SID 82 Digest, 13, 156-157

30   (1982), uses an empirically derived parameter for tail breakoff time, T_b, given by

$$T_b = A + B(\mu d)/\sigma,$$

where d is the nozzle diameter, μ is the fluid viscosity, and A and B are fitting parameters. In one example, A was determined to be 47.71 and B to be 2.13. In this example, for a nozzle diameter of 50 microns, viscosity of 10 centipoise and a surface tension of 30 dyn/cm, the tail breakoff time is about 83 microseconds.

The Rayleigh criterion for stability of a laminar jet of fluid can be used to estimate a range of firing frequencies over which individual droplet formation can be optimized. This criterion can be expressed mathematically as

$$k = \pi d/\lambda.$$

Here, k is a parameter derived from the stability equation for a cylindrical jet of fluid. The stability of the jet is determined by whether a surface perturbation (such as a disturbance created by a pulse) will grow in amplitude. λ is the wavelength of the surface wave on the ejector. The parameter k should be between zero and one for the formation of separate drops. Since λ is equal to the droplet velocity, v, divided by the pulse frequency, f, this equation can be recast in terms of frequency and velocity. Thus, for formation of separate droplets

$$f \leq v/(\pi d).$$

For example, in an ejector where $d = 50$ microns, and $v = 8$ m/s, according to this analysis f should be less than about 50 kHz for effective droplet separation. In this example, a multipulse fire frequency of approximately 60 kHz should help provide single droplets for a multipulse waveform.

The mass of each droplet can be varied by varying the number of pulses in the multipulse waveform. Each multipulse waveform can include any number of pulses (e.g., two, three, four, five, or more pulses), selected according to the droplet mass desired for each droplet jetted.

In general, droplet mass can vary as desired. Larger drops can be generated by increasing pulse amplitudes, pulse widths, and/or increasing the number of fire pulses in the multipulse waveform. In some embodiments, each ejector can eject drops that vary over a range of volumes

such that the mass of the smallest possible droplet is about 10 % of the largest possible droplet mass (e.g., about 20%, 50%). In some embodiments, an ejector can eject drops within a range of droplet masses from about 10 to 40 picoliter, such as between about 10 and 20 picoliter. In other embodiments droplet mass can be varied between 80 and 300 picoliter. In further embodiments, droplet mass may vary between 25 and 120 picoliter. The large variation in possible droplet size may be particularly advantageous in providing a variety of gray levels in applications utilizing gray scale printing. In some applications, a range of about 1 to 4 on droplet mass with two mass levels is sufficient for effective gray scale.

A pulse train profile can be selected to tailor further droplet characteristics in addition to droplet mass. For example, the length and volume of a droplet's tail can be substantially reduced by selecting an appropriate pulse train profile. A droplet's tail refers to a volume of ink in the droplet that trails substantially behind the leading edge of the droplet (e.g., any amount of fluid that causes the droplet shape to differ from essentially spherical) and will likely cause performance degradation. Fluid that is more than two nozzle diameters behind the leading edge of the droplet typically has a detrimental impact on performance. Droplet tails typically result from the action of surface tension and viscosity pulling the final amount of fluid out of the nozzle after the droplet is ejected. The tail of a droplet can be the result of velocity variations between different portions of a droplet because slower moving ink ejected from the orifice at the same time or later than faster moving ink will trail the faster moving ink. In many cases, having a large tail can degrade the quality of a printed image by striking a different portion of a moving substrate than the leading edge of the droplet.

In some embodiments, the tail can be sufficiently reduced so that jetted drops are substantially spherical within a short distance of the orifice. For example, at least about 60% (e.g., at least about 80%) of a droplet's mass can be included within a radius, r, of a point in the droplet, where r corresponds to the radius of a perfectly spherical droplet and is given by

$$r = \sqrt[3]{\frac{3}{4\pi}\frac{m_d}{\rho}} ,$$

where m_d is the droplet's mass and ρ is the ink density. In other words, where at least about 60% of the droplet's mass is located within r of a point in the droplet, less than about 40% of the

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droplet's mass is located in the tail. In some embodiments, less than about 30% (e.g., less than about 20%, 10%, 5%) of the droplet's mass is located in the droplet tail. Less than about 30% (e.g., less than about 20%, 10%, 5%) of the droplet's mass can be located in the droplet tail for droplet velocities more than about 4 ms^{-1} (e.g., more than about 5 ms^{-1}, 6 ms^{-1}, 7 ms^{-1}, 8 ms^{-1}).

5   The proportion of fluid in the droplet tail can be determined from photographic images of droplets, such as those shown in FIG. 15A – B and FIG. 16A – B. In particular, the proportion of fluid in the droplet tail can be extrapolated from the relative area of the droplet body and droplet tail in the image.

       Pulse parameters influencing droplet characteristics are typically interrelated.

10   Furthermore, droplet characteristics can also depend on other characteristics of the droplet ejector (e.g., chamber volume) and fluid properties (e.g., viscosity and density). Accordingly, multipulse waveforms for producing a droplet having a particular mass, shape, and velocity can vary from one ejector to another, and for different types of fluids.

       Although multipulse waveforms described previously consist of continuous pulses, in

15   some embodiments, an ejector can generate a droplet with a multipulse waveform that includes discontinuous pulses. Referring to FIG. 12, an example of a multipulse waveform that includes discontinuous pulses is multipulse waveform 500, which includes pulses 510, 520, 530, and 540. The first pulse 510 of the total waveform is separated from the second pulse 520 of the total waveform by a null period, 512. The second pulse 520 is separated from the third pulse 530 by a

20   null period 522. Similarly, the fourth pulse 540 is separated from the third pulse 530 by null periods 532. One way of characterizing the relationship between pulse period and delay period is by the pulse duty cycle. As used herein, the duty cycle of each pulse refers to the ratio of the pulse period to the period between pulses (i.e., pulse period plus delay period). A duty cycle of one, for example, corresponds to pulses with zero delay period, such as those shown in FIG. 4A.

25   Where pulses are separated by a finite delay period, the duty cycle is less than one. In some embodiments, pulses in a multipulse waveform may have a duty cycle of less than one, such as about 0.8, 0.6, 0.5 or less. In some embodiments, delay periods can be utilized between waveforms to reduce the effect of interference between subsequent pulses and earlier pulses. For example, where damping of the reflected pulse is low (e.g., where the ink viscosity is low), it

30   may be desirable to offset adjacent pulses in time to reduce these interference effects.

Referring to FIG. 13 and FIG. 14, during printing using an ink jet printhead, multiple drops are jetted from each ink jet by driving the ink jet with multiple multipulse waveforms. As shown in FIG. 13, multipulse waveforms 810 and 820 are followed by delay periods 812 and 822, respectively. One droplet is ejected in response to multipulse waveform 810, and anther

5   droplet is jetted in response to multipulse waveform 820. Generally, the profile of adjacent multipulse waveforms can be the same or different, depending on whether or not similar drops are required.

The minimum delay period between multipulse waveforms typically depends on printing resolution and the multipulse waveform duration. For example, for a relative substrate velocity

10   of about one meter per second, multipulse waveform frequency should be 23.6 kHz to provide a printing resolution of 600 dpi. Thus, in this case, adjacent multipulse waveforms should be separated by 42.3 microseconds. Each delay period is thus the difference between 42.3 microseconds and the duration of the multipulse waveform.

FIG. 14 shows an example of an ink jet jetting multiple drops from a circular orifice

15   having a 23 μm diameter. In this embodiment, the drive pulses were approximately 16 microseconds in duration and 25 microseconds apart, due to a firing rate of 40 kHz.

FIG. 15A – B and FIG. 16A - B show comparisons of two jets firing 80 picoliter drops at two different frequencies. One jet, shown in FIG. 15A and 16A, is a smaller jet (nominally 20 picoliters) and uses a four pulse waveform to eject an 80 picoliter droplet. The other jet, shown

20   in FIG 15B and 16B, is an 80 picoliter jet using a single pulse waveform. The droplets formed with multipulse waveforms also exhibit reduced tail mass compared to those formed with single pulse waveforms.

In general, the drive schemes discussed can be adapted to other droplet ejection devices in addition to those described above. For example, the drive schemes can be adapted to ink jets

25   described in U.S. Patent Application Serial No. 10/189,947, entitled "PRINTHEAD," by Andreas Bibl and coworkers, filed on July 3, 2003, and U.S. Patent Application Serial No. 09/412,827, entitled "PIEZOELECTRIC INK JET MODULE WITH SEAL," by Edward R. Moynihan and coworkers, filed on October 5, 1999, the entire contents of which are hereby incorporated by reference.

30   Moreover, as discussed previously, the foregoing drive schemes can be applied to droplet ejection devices in general, not just to those that eject ink. Examples of other droplet ejection

apparatus include those used to deposit patterned adhesives or patterned materials for electronic displays (e.g., organic LED materials).

A number of embodiments of the invention have been described. Nevertheless, it will be understood that various modifications may be made without departing from the spirit and scope

5   of the invention. Accordingly, other embodiments are within the scope of the following claims.